(12) UK Patent Application (19) GB (11) 2 328 342 (13) A

(43) Date of A Publication 17.02.1999

(21) Application No 9717022.9

(22) Date of Filing 13.08.1997

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(51) INT CL[6]
E21B 6/00, B06B 1/08, E21B 1/00

(52) UK CL (Edition Q)
H4J JCD J31C
E1F FEJ
U1S S1647 S1747

(56) Documents Cited
WO 97/26090 A1

(58) Field of Search
UK CL (Edition P) H4J JCD
INT CL[6] B06B 1/08, B25D 11/00 11/02 11/04 11/06 16/00, B28D 1/14, E21B 1/00 4/04 4/12 6/00, H01L 41/12
ONLINE: WPI, JAPIO, CLAIMS

(54) Abstract Title

Magnetostrictive actuator

(57) A magnetostrictive actuator that may be used in a percussive rock drill. The actuator comprises a percussive tool 2,3 for working a rock face 1, biasing means 10 arranged to apply a biasing force to the tool 2,3, and a magnetostrictive unit 4 arranged to apply a repetitive pulsating force to the tool 2,3 for working the rock face 1, the magnetostrictive unit 4 having a length of magnetostrictive material 13 and drive means 12 for subjecting the material 13 to a pulsed magnetic field to produce a change in the length of the material on each pulse of the magnetic field and so produce the pulsating force. The arrangement is such that the biasing force is not transmitted to the tool 2,3 through the length of magnetostrictive material 13, and so damage to the magnetostrictive material may be prevented.

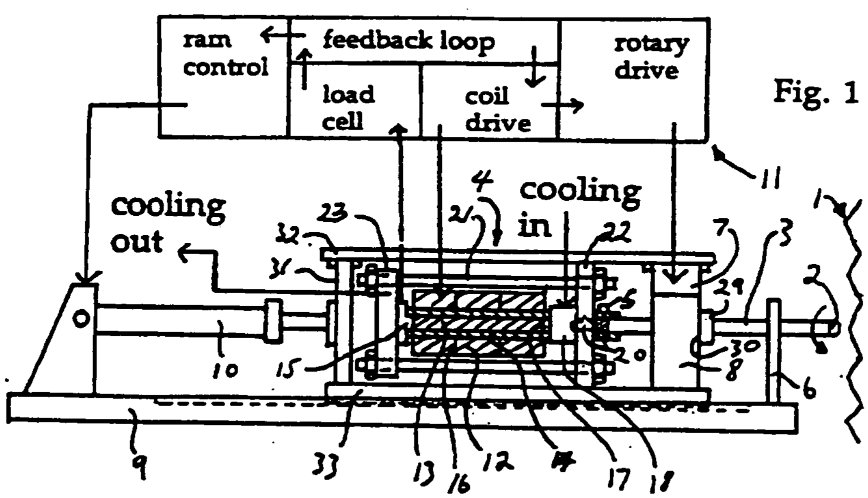

Fig. 1

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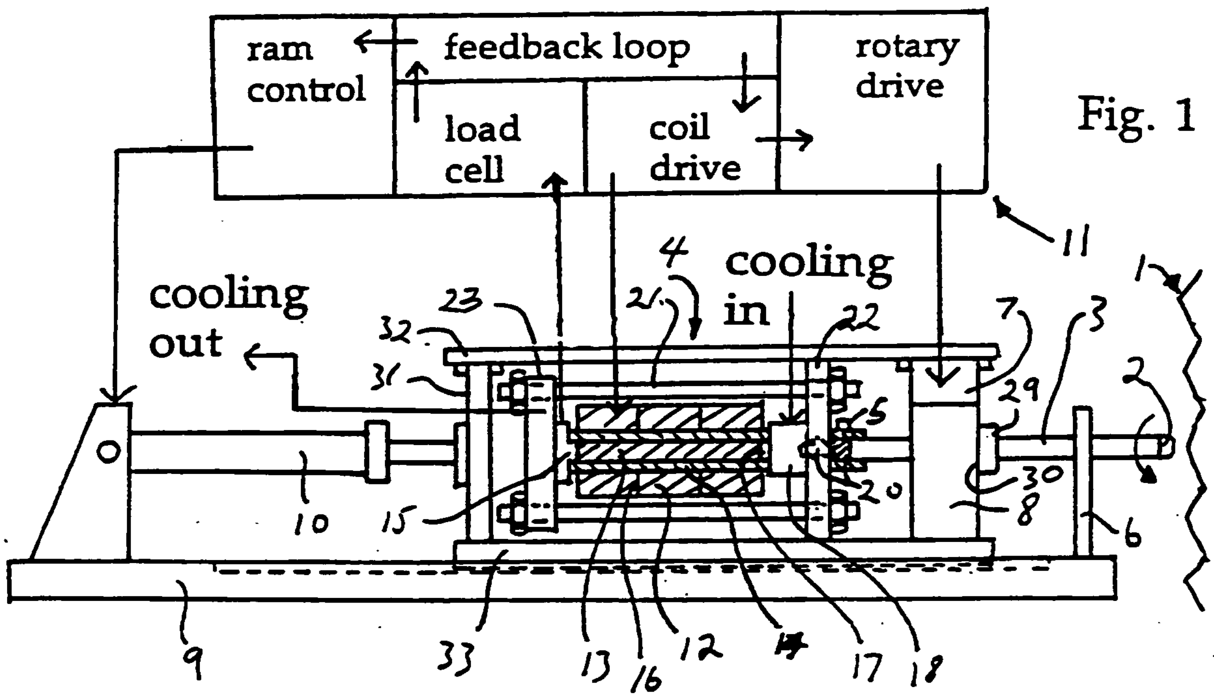

ram control
feedback loop
rotary drive
load cell
coil drive
cooling out
cooling in
4
11
1
2
3
5
6
7
8
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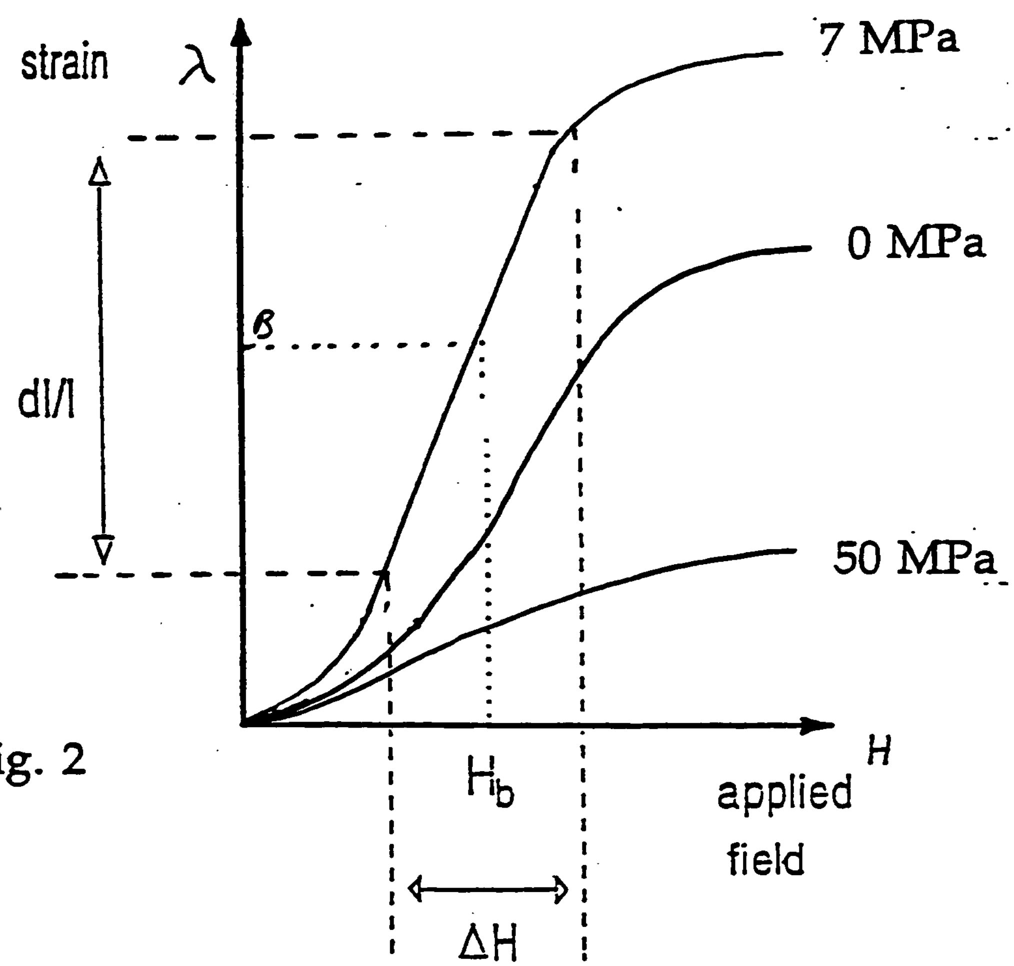
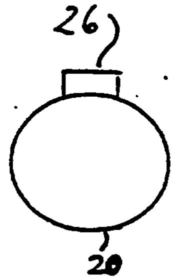
Fig. 1



strain λ
7 MPa
0 MPa
50 MPa
dl/l
B
H_b
H
applied field
ΔH

Fig. 2

Fig. 3a



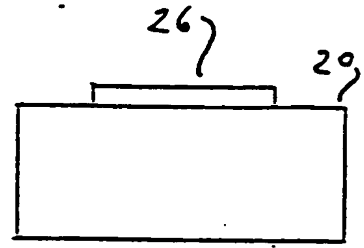


Fig 3b

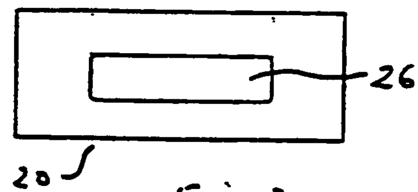


Fig 3c

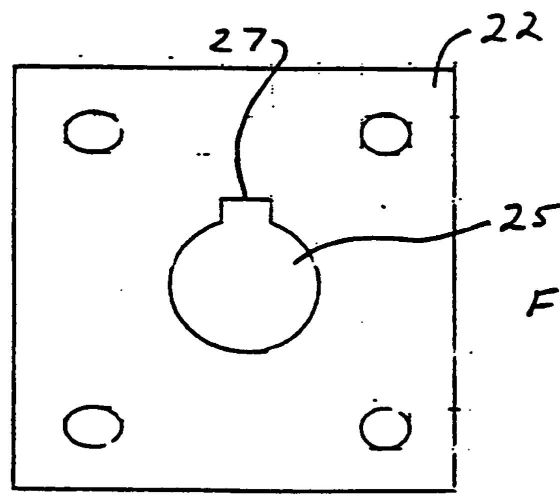


Fig 4

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Magnetostrictive Actuator

This invention relates to a magnetostrictive actuator, and in particular to a magnetostrictive actuator that may be used in a percussive rock drill.

In a percussive rock drill, a drill bit is repeatedly forced against a rock surface, whilst being rotated about its own axis. This produces high local stresses in the rock surface which cause the rock to fracture. The fractured rock is flushed away from the bit surface and back along the drilled hole by a flushing fluid introduced for that purpose.

It is conventional to use hydraulic energy to move a hammer backwards and forwards against the drill bit to produce the percussive action. However the use of hydraulic energy in this way produces efficiency levels which are lower than could be desired, and the necessity to route hydraulic hoses to and from the hammer unit can cause problems.

It is known that a magnetostrictive actuator may be used in a rock drill. One example of a prior art magnetostrictive actuator for use in a rock drill is disclosed in the patent document SU 454 329-A. The actuator has a cylindrical shape and comprises a magnetostrictive material having a negative magnetostrictive coefficient, so that the material contracts upon the application of a magnetic field. A problem with this type of actuator, described in patent document SU 424 969-A, is that the magnetostrictive material in the actuator may fracture during drilling if the axial pressure falls suddenly due to a sudden change in the hardness of the rock being worked, and therefore

an automated feeding system is proposed which reduces the drive current to coils upon loss of axial pressure.

It is known that some types of magnetostrictive material are brittle, in particular those noted for their large strain coefficients and high magnetic-mechanical conversion efficiencies such as those sold under the trade mark Terfenol.

It has been proposed to use a positive coefficient magnetostrictive material which lengthens upon application of a magnetic field. One such type of actuator is disclosed in patent document SU 553 013-A, in which a central rod of magnetostrictive material is driven by a single coil wrapped around the length of the material.

Another such magnetostrictive actuator is disclosed in SU 956 050-A. In this actuator two adaptor plates are fixed to the ends of a magnetostrictive core. One plate is intended to connection to a rock-breaking tool (eg a drilling string), and the other plate is for connection via a shock absorber to the drive (eg a hydraulic ram) so that the actuator is in-line between the drive and tool.

A problem with all such in-line arrangements is that the stresses in the magnetostrictive materials will depend upon a combination forces imparted by the drive acting axially through the material, the forces generated internally by the magnetostrictive action, and the hardness of the rock being drilled at any instant. In order to guard against fracture of the magnetostrictive material, it may not always be possible to run the magnetostrictive material at full power. Furthermore, it may not always be possible to run the magnetostrictive material at full efficiency, since the efficiency of

conversion of magnetic energy into pulsating energy depends upon the axial stresses in the magnetostrictive rod.

According to the present invention, there is provided a magnetostrictive actuator for applying a pulsating pressure to a work piece, comprising a percussive tool for working the workpiece, biasing means arranged to apply a biasing force to the tool for biasing the tool against the work piece, a magnetostrictive unit arranged to apply a repetitive pulsating force to the tool for working the workpiece, the magnetostrictive unit having a length of magnetostrictive material and drive means for subjecting the material to a pulsed magnetic field to produce a change in the length of the material on each pulse of the magnetic field and so produce the pulsating force, wherein the arrangement is such that the biasing force is not transmitted to the tool through the length of magnetostrictive material.

If the magnetostrictive material has a positive magnetostrictive coefficient of expansion, then each pulse of the magnetic field, whether in a positive or a negative direction, will result in an expansion in length of the magnetostrictive material. The length of material may be shaped as a rod, or a bundle of rods, each with a suitable cross-section, such as circular, square or hexagonal. The expansion of the length of rod will then produces a corresponding movement of an end of rod, so producing the pulsating force.

Also according to the invention, there is provided a magnetostrictive rock drill, comprising a magnetostrictive actuator for applying a pulsating pressure to a rock face, a percussive tool for working the rock face, biasing means

arranged to apply a biasing force to the tool for biasing the tool against the rock face, a magnetostrictive unit arranged to apply a repetitive pulsating force to the tool for working the rock face, the magnetostrictive unit having a length of magnetostrictive material and drive means for subjecting the material to a pulsed magnetic field to produce a change in the length of the material on each pulse of the magnetic field and so produce the pulsating force, wherein the arrangement is such that the biasing force is not transmitted to the tool through the length of magnetostrictive material.

The percussive tool may then be arranged so that it may force a bit with sufficient pressure against the rock face to fracture the rock when the percussive force and the biasing force are applied in conjunction.

The biasing means may include a ram, such as a hydraulic ram to provide the biasing force.

The action of the movement of the magnetostrictive unit causes the percussive toll or drill bit to be forced against the rock. In a typical rock drill installation, the drill bit will be at one end of a drill string and the magnetostrictive material will be arranged so that it applies a force to the other end of the drill string. Thus the magnetostrictive material may be "down the hole" and directly behind the drill bit or it may alternatively be spaced from the drill bit by a considerable length of compression pulse transmitting drill rods.

In general, the presence of the drill bit, rods, etc., will affect the resonant frequency response of the mechanical system including the magnetostrictive unit. The unit may, optionally, be run at or near a mechanically

resonant frequency for the system in order to improve the efficiency of the conversion of pulsating energy into working of the work piece.

Preferably, the biasing means has a coupler, such as a flange, plate or other such engaging means, arranged to bear upon the tool to bias the tool towards the work piece. The magnetostrictive unit may then being affixed the coupler so that the coupler provides a restoring force to any force generated by the magnetostrictive material.

In a preferred arrangement, the coupler comprises a gear box assembly, the front face of which bears against shoulder on the tool.

In a preferred embodiment, there is an aperture through the coupler, through which the tool extends. The magnetostrictive unit may then have means, for example a projecting end piece which extends to reach the tool, for applying the pulsating force to the percussive tool. The percussive force may then be provided in parallel, rather than in-line, with the biasing force.

It is advantageous if the magnetostrictive material is pre-stressed or pre-loaded along the length of the material when the drive means is not subjected to the pulsed magnetic field. This is because a force along the length of the magnetostrictive material will, up to a certain pressure, improve the efficiency with which magnetic energy is converted into pulsating energy. The pre-stress may be a compressive force along the length of the magnetostrictive material generated, for example, by a spring biasing means acting on an end of the magnetostrictive material, either in direct contact with the material or through an intervening component.

In order to simplify construction, improve maintenance and repair, and to reduce operating voltages, the drive means may comprise a plurality of coils arranged to provide a magnetic field along the length of the magnetostrictive material. The operating voltage may be reduced if the coils can be arranged so that the coils are at least partially inductively decoupled, for example with intervening flux closure elements placed between adjacent coils. In a preferred embodiment, there are just three coils.

The multiple coils may be driven by a single drive circuit, but it is advantageous in order to lower the amount of current or power that has to be delivered by a drive circuit if each coil has its own drive circuit, which may then be individually controllable by the drive means.

The drive circuit will typically be supplied by a fixed voltage ac power source, although the drive circuit could be designed to run from a variable voltage source, with the drive circuits supplying current to the coils, for example through FETs. The coils may also be driven in electrical resonance.

Multiple coils can each have a lower individual inductance than a corresponding single coil, which permits lower coil driving voltages and/or faster current rise times and consequent higher achievable pulsating frequency.

Each coil may conveniently be the same as every other coil, having the same dimensions and number of turns, in order to simplify manufacture or repair of the magnetostrictive unit.

The magnetostrictive material is preferably held within a sleeve which is close fitting around the sides of the material and open at the ends. The ends of the material may also bear against end pieces, one of the end pieces being fixed and another of the end pieces being movable upon a change in the length of the magnetostrictive material in order to apply the pulsating force to the percussive tool. The sleeve may align and at least partially enclose the end pieces.

End plates may be provided to hold the coils in place within the magnetostrictive unit. The end pieces, end plates, and particularly the sleeve have to hold the magnetostrictive material securely in order to prevent bending and consequent fracturing of the material under the high compressive stresses present during actuation.

The coils may be integrally bonded one with another, but it is generally preferred if the coils are held securely and separable from each other. For example, the coils may be separated by spacer elements which extend from the sleeve. Then if a coil fails for any reason, the magnetostrictive unit may be disassembled to replace or repair the defective coil, without having to discard the complete coil assembly.

The spacers may conveniently be integral with the flux closure elements. For example, the spacers could be steel shims or discs and may optionally provide additional electrical insulation between the coils. Alternatively, the spacers could comprise a non-magnetic metal, which may have a higher thermal conductivity than steel, such as copper. The shielding effect of one coil from another may then be provided at the drive frequency by the skin effect in the surfaces of the copper adjacent to neighbouring

coils.

During operation of the actuator, heat will be generated in the magnetostrictive unit from such sources as electrical resistance in the coils and eddy currents generated by self-inductance between coils and in conductive components including the magnetostrictive material itself. Above a certain operating temperature, the coils may become damaged, and the efficiency of the magnetostrictive actuator may drop off. In order to achieve a sufficiently high actuation rate, it will for many applications be necessary to have a cooling circuit that circulates a gas or liquid cooling fluid, such as air, oil or water, through the applicator to remove excess heat from the magnetostrictive unit.

To improve the efficiency of the cooling, the cooling circuit may be incorporated with the spacers or the flux closure elements to cool between the coils, and to remove excess heat from the magnetostrictive material inside the coils. The coolant may flow inside channels in the spacers, or alternatively if the spacers have a high enough thermal conductivity, the spacers may simply conduct heat out of the coil assembly towards the cooling circuit.

The sleeve may also contain cooling channels as part of the cooling circuit.

If the current pulses all have the same polarity, then the magnetostrictive unit will be pulsed once for each cycle of the drive frequency. In this case, each pulse may last for about a half-cycle.

However, current may be pulsed in both positive and

negative directions so that the frequency of the magnetostrictive unit may be doubled relative to the drive frequency. In this case each of the two mechanical pulses per cycle may last about one-quarter cycle. The actuation rate may therefore be effectively doubled, without the need for using a higher drive frequency with the consequent need for higher drive voltages and/or lower coil impedances.

Ideally, the magnetic field applied to the magnetostrictive material should not drop off towards the ends of the coil arrangement. Although the magnetic field may be substantially constant through the middle of the magnetostrictive material, field lines may diverge at the coil ends so reducing field strength. In order to ameliorate this effect and produce a more even magnetic field profile along the length of the magnetostrictive material and so optimise the performance of the magnetostrictive unit throughout its length, the drive means may optimally be arranged to supply more current to the coils nearer the coil ends than to coils farther from the coil ends. The amount of the current may be increased either by increasing a drive voltage supplied by the drive means, or by increasing the on/off duty cycle of the current. Alternatively, the current may not be varied, and the dimensions of the coils or the number of turns may be varied towards the ends of the coil arrangement.

The ability to control the amount of current provided to each coil may also be used to compensate for changes in relative permeability along the length of the magnetostrictive material due to such factors as variation in composition, or crystal grain misalignment.

When the coils are separately driven, the drive means may

actuate coils with drive current at different times. By independently controlling the on and off time of each pulse different coils may be driven at different duty cycles.

The on and off times may be varied in a synchronised manner from one end of the magnetostrictive unit to the other, so that the on times from one coil to the next are delayed by an interval comparable with speed of sound in the magnetostrictive material. It may then be possible to produce a travelling mechanical wave pulse along the length of the magnetostrictive material, as each coil is successively actuated in turn. This results in a superimposing effect with the pulsating mechanical pulses arising from each coil arriving at the end of the magnetostrictive unit or applicator essentially superimposed and so increasing the pulsating pressure that may be applied.

The magnetostrictive unit may also be driven in mechanical resonance, so that the drive frequency matches the natural frequency of longitudinal compressive waves for the actuator. Resonant operation improves the efficiency of the actuator by increasing the amplitude of the pulsating action and/or decreasing the required electrical drive power. The resonant frequency of the magnetostrictive unit will, in general, be affected by the presence of other items in contact with the magnetostrictive unit, such as the biasing means.

In another arrangement, the drive circuitry has means to modulate the drive current during a current pulse in order to modulate similarly the pressure applied by the magnetostrictive unit.

It is preferred if the magnetostrictive unit comprises a gauge or load cell, which is preferably in contact with one end of the magnetostrictive material, to measure the pressure of the pulsating force, and also feedback means for controlling this pressure. The gauge or load cell may provide a signal representative of the pulsating pressure to the feedback means which then uses this signal to control the pulsating pressure. The control may be the magnitude of the force, or the rise time, or some other parameter associated with the total energy supplied by the pulse.

Because the instantaneous pressure will vary rapidly during one cycle of the magnetostrictive unit, the signal from the gauge may most usefully be an average over several cycles.

The feedback means may be arranged to increase the pressure or compressive force exerted by the biasing means if the measured pressure falls below a predetermined point. This feedback is advantageous because it helps to protect a magnetostrictive rod from mechanical failure. The feedback means may then be arranged to control both the pre-stress in the magnetostrictive material and the thrust applied to a drill bit.

The feedback means may, of course, provide the inverse feedback upon an increase in the average pressure measured by the gauge.

In a further embodiment of the invention, instead of a fixed voltage and frequency ac power source, the applicator comprises an electric generator for synchronously driving the drive means at the drive frequency. The generator may be driven by a hydraulic

supply line, so avoiding the need to run electric cables long distances to the actuator.

The generator may conveniently be driven at a frequency in direct proportion to the frequency of the actuator. An advantage of this approach is that to obtain higher frequencies, the generator merely has to be operated faster. At higher frequencies the inductance of the coil causes the coil's impedance to rise. Fortuitously, when a generator is run at a greater speed, it produces the greater voltages necessary to overcome the higher impedance and produce the desired magnetic field at the increased frequency. In other words, the output voltage from an electric generator varies proportionately with the generator frequency in the same ratio as the optimum drive voltage for a coil needed to keep the current rise time within the coil to a constant fraction of the period of the coil drive frequency. The drive means may therefore automatically be arranged to increase the coil drive voltage.

The magnetic field may be pulsed at a frequency varying between or set between 0 and 1 kHz, although in some applications a pulsating frequency of up to about 2 kHz may be desirable. Preferably, the magnetic field is pulsed at a frequency of at least 30 Hz.

The magnetostrictive material is preferably that known under the trade mark Terfenol. This is a metallic compound containing the rare earth elements dysprosium and terbium, together with iron. Terfenol has very good magnetostrictive properties, that is, it produces a relatively high change in length on application of a magnetic field. This change in length can be about 0.1 percent.

Also according to the invention, there is provided a magnetostrictive rock drill, comprising a drill bit adapted to bear against the rock, and a magnetostrictive actuator for applying a pulsating pressure, comprising an applicator with a magnetostrictive unit having a length of magnetostrictive material and drive means for subjecting the material to a pulsed magnetic field to produce a change in the length of the material on each pulse of the magnetic field, characterised in that the drive means has a plurality of coils supplied in parallel with an electric drive current pulsed at a drive frequency from one or more drive circuits, the magnetostrictive actuator being arranged so that it may force the bit with sufficient pressure to fracture the rock.

The voltage required of the power source or from the drive circuits may be minimised if the inductance of the coils are suitably reduced by minimising the number of turns on the coils. Another way of minimising the voltage is to add capacitance to the drive circuits so that the coils may be driven in electrical resonance at the drive frequency.

A gearbox is preferably provided between the magnetostrictive unit and the drill bit, to rotate the drill bit as the pulsating force is being applied.

The use of multiple coils permits the impedance of each coil to be reduced in comparison with the impedance of a single equivalent coil. A lower impedance is desirable because it permits during a current pulse a relatively faster rise time for a given voltage provided by the drive circuitry. A faster rise time permits a greater drive frequency and hence a higher and more efficient drilling rate. Higher voltages, and particularly voltages above

1 kV are undesirable owing to the greater difficulty of safely insulating electrical components or running electrical cables in a mining environment which may, in some cases, be very humid and hot.

The invention will now be further described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a schematic block diagram showing a magnetostrictive rock drill according to the invention, having a magnetostrictive unit with associated electronics, the magnetostrictive unit shown partly in cross-section;

Figure 2 is a graph showing the relationship between strain and applied magnetic field for a magnetostrictive material;

Figures 3a, 3b, and 3c show, respectively, end, side and top side views of an anti-rotation element; and

Figure 4 shows an end plate with a keyed hole in which the anti-rotation element is seated.

Figure 1 shows a rock face 1 to be drilled, with a drill bit 2 about to be placed in initial contact with this rock face. The bit 2 is mounted at the end of a drill rod 3, the other end of which terminates in a pulsating force magnetostrictive unit generally indicated at 4.

As drilling proceeds, the bit 2 will form a hole in the rock face 1. Depending on the length of the hole to be drilled, it may be necessary to interrupt the rod 3 to extend it by inserting further lengths of drill rod in a

known manner.

Also in a known manner, the fractured rock is flushed away from the bit surface and back along the drilled hole by a flushing fluid such as air or water ejected through the drill bit. The fluid is introduced for that purpose into the base of the drill rod 3 at an inlet 5 in a so-called water box.

The drill rod 3 is supported by and passes through a mount 6 and a hydraulic motor gearbox 8. The gearbox 8 is connected to a hydraulic motor 7 for rotating the drill rod 3 and bit 2. A shoulder 29 on the drill rod 3 rests on a front face 30 of the gear box 8.

The magnetostrictive unit 4 is slidably mounted on a fixed beam 9 on which a hydraulic ram 10 applies a thrusting bias pressure to the back of the magnetostrictive unit 4, and moves the unit forward as the drill bit 2 cuts into the rock 1. A fatigue rated load cell 24 is mounted between the ram 10 and the actuator assembly 4.

When the ram thrusts the magnetostrictive unit 4 forwards, the force is transmitted to the drill rod 3 through the frame of the unit, comprising back, top and bottom plates 31,32,33 to the gearbox at the front of the frame, and thence to the drill string by the contact between the shoulder 29 and front gearbox face 30. The thrusting bias force thereby bypasses the magnetostrictive material, explained in more detail below.

Control and drive electronics are shown schematically for a closed loop system and generally indicated at 11. The electronics 11 may, of course, be conveniently integrated in a separate unit mounted on the beam 9 in proximity with

the magnetostrictive unit 4.

Magnetostriction is the fractional change in length of a material obtainable by the application of a magnetic field. It is usually anisotropic and volume conserving. The magnetostrictive material in the magnetostrictive unit is known and sold under the trade mark Terfenol-D ($Tb_xDy_{1-x}Fe_y$ where $0.27 \leq x \leq 0.32$ and $1.92 \leq y \leq 2.0$). Terfenol-D can withstand a high uniaxial stress of up to 350 MPa. The tensile strength however, is only, at most, 25 MPa.

Figure 2 shows the general Strain λ vs. Magnetic Field H relationship for Terfenol-D at different levels of pre-stress. The magnitude and efficiency of the achievable strain for a given magnetic field is a maximum if a pre-stress of about 7 to 15 MPa is first applied. This is due to magnetoelastic effects. Strains λ greater than 0.1% can readily be achieved in Terfenol-D with moderate magnetic fields of about 120 kA/m.

The efficiency of the conversion of magnetic energy into strain is greatest where the slope of the curve is maximum at point H_b. For some applications it may be desirable to pre-stress or pre-load the Terfenol-D with a compressive force in the approximately linear region at the point B on the curve, either with static magnets or with a constant bias current in a coil arrangement.

When using Terfenol-D for rock drilling, it is desirable to pre-stress the material to approximately 15 to 30 MPa. The optimum level of pre-stress will depend upon the grain structure and other characteristics of the magnetostrictive material.

A simple calculation illustrates the feasibility of using

a Terfenol based actuator to drill rock. A 500 mm long rod of Terfenol-D may expand upon application of the field by 0.5 mm. A conventional drill bit may have a contact area A_c with rock of $6.6x10^{-5}$ m^2 upon penetrating the rock by 0.5 mm. The required force needed to achieve 140 MPa pressure would then be 9257 N. Under steady state conditions, the force applied by the Terfenol-D will be $F=E\times A_r\times\lambda$, where E is Young's Modulus which is estimated to be about 30 GPa, A_r is the cross-sectional area of the rod which is here 20 mm in diameter, and λ is 0.1%. The available magnetostrictive force is then 9425 N, which is more than sufficient to fracture such rock, even before taking into consideration the additional force available from the pre-stress.

Returning now to Figure 1 to consider in more detail the construction and operation of the magnetostrictive unit 4 and the interface of this unit to the drill rod 3 and hydraulic ram 10, the unit 4 has a generally cylindrical set of three coils 12. A magnetostrictive Terfenol-D rod 13 lies on the axis of the coils, and is held securely in a close fitting non-magnetic support sleeve 14.

One end of the magnetostrictive rod abuts an end piece 15 in the form of a cylindrical hardened steel load cell which extends partly into the sleeve 14, and the other end of the magnetostrictive rod is free to expand and contract a limited distance in contact with another cylindrical end piece 17, also extending partly into the sleeve and made from form hardened steel. The sleeve 14 extends beyond the ends of the Terfenol-D rod 13 in order to hold and align the end pieces 15,17.

The movable end piece 17 in turn contacts a pre-stress spring assembly 18, which has a disk spring stack inside

that pre-stresses the Terfenol-D to point "B" shown on the graph of Figure 2. With reference now also to Figures 3a, 3b,3c and 4, the disk spring stack in turn contacts an anti-rotation keyed device 20 which is slidably seated in a keyed hole 25 in a plate 22. The plate 22 is joined by four steel rods 21 which extend parallel to the axis of the Terfenol-D rod to a similar parallel plate 23. The assembly comprising the Terfenol-D rod 13, sleeve 14, end pieces 15,17 and pre-stress spring assembly 18 is therefore contained and kept under axial compressive stress between the parallel plates 22,23, and this axial stress is independent of the thrusting bias provided by the ram 10 to the drill rod 3.

The axial movement of the Terfenol-D rod 13 is therefore transmitted through the movable end piece 17, pre-stress spring assembly 18 and anti-rotational element 20 to the drill rod 3.

The anti-rotational element 20 decouples the rotary motion of the drill bit from the magnetostrictive actuator material 13. The anti-rotational element 20 consists of a cylindrical body. A key 26 protrudes radially outwards from the cylindrical body section. The keyed section mates with a recess 27 in the hole 25 through the plate 22. This arrangement prevents rotary motion from being transferred onto the Terfenol-D rod 13 whilst it allows the axial expansion and contraction of the magnetostrictive rod to be transferred to the drill rod 3. At the same time, this arrangement effectively decouples the thrusting bias of the ram from the pre-stress bias of the magnetostrictive material.

Referring now again to Figure 1, the sleeve 14 is formed from a resilient glass fibre reinforced plastics material

such that sold under the trade mark Tufnol, grade 10G/40. The Terfenol-D rod 13 may shatter if it is forced out of alignment during assembly or during pulsed operation of the magnetostrictive unit. In order to constrain the rod from bending during operation the tolerance between the sleeve and rod should be as close as possible, and ideally the sleeve should be stiff, too. However, these two requirements are incompatible with the relative fragility of the Terfenol-D rod which, for example, may shatter owing to inadvertent bending during insertion into a close fitting metal or ceramic sleeve. The sleeve may also have to support at least some of the weight of the coil assembly which surrounds it, at least during assembly of the magnetostrictive unit. A tough plastic sleeve has therefore been found to have a good combination of properties for this application.

As a more durable alternative to Tufnol plastic, a ceramic material may be used for the sleeve.

Each of the coils 13 is separated from its neighbour by dividing plates having a central circular hole for the sleeve. These plates serve two purposes. Firstly, they help to support the weight of the coils, reducing flexing of the support sleeve 14 and magnetostrictive material 13. Although the magnetostrictive material has high strength in compression, it is weak in terms of sheer strength. Secondly, the plates reduce effects of mutual inductance and enhance magnetic field profile by reducing reluctance.

The coil dimensions are an inside diameter of 40 mm, an outer diameter of 100 mm, a coil length of 160 mm. With a wire diameter of 2.2 mm, each coil has a resistance of 0.9 Ω and an inductance L of 20 mH. The coils were capable of producing a field of 7.5 $kAm^{-1}A^{-1}$. Using the

power amplifiers developed for this application, a field of 75 kAm^{-1} could be developed at frequencies in excess of 400 Hz. To generate this level of field the power amplifiers consumed 2 kW per coil, amounting to a total of 6 kW for the full three coil actuator assembly.

The actuator did not incorporate any d.c. magnetic bias field, thus, the actuator generated force for both the positive and negative constituents of the drive waveform. Therefore, the system mechanically rectified the input field to generate a pulsating force at double the electrical input frequency.

At a 1 kHz sine wave electrical frequency f, the reactance $2\pi fL$ of each coil would be 126 Ω. Operation can be achieved at a supply current of about 10 A rms, and since the power requirement equates to the energy stored in each coil, $\frac{1}{2} LI^2 = \frac{1}{2} \cdot (20\ mH) \cdot (14\ A^2) = 1.96\ J$ (per coil). Thus, at 1 kHz the three coils would consume approximately 6 kW, this includes heating losses, (I^2R).

The three coils are then assembled over the sleeve with spacers 16 between each coil. Although not illustrated, the coil assembly is then encased in an outer protective cylindrical steel shell, which provides flux closure. This shell may also have a protective outer protective plastic envelope. The steel tie rods 21 will also contribute to closing the magnetic circuits for each coil.

If an electrical fault in a coil develops later on, the magnetostrictive unit 4 may be readily disassembled and the defective coil replaced.

The use of a plurality of coils, each independently supplied with current, allows the operating voltage for

each coil to be lower than for an equivalent single coil. A magnetostrictive rock drill may have a pulsating frequency of about 1 kHz for a high drilling rate. For a single coil magnetostrictive actuator, this would imply an operating voltage of several kilovolts owing to the high coil impedance.

Mutual inductance between coils of a multiple coil arrangement would make the inductance comparable with a single coil arrangement. To minimise this self-coupling effect, the spacers 16 need to made from a magnetic material, such as steel coated with an insulating material, in order to direct flux closure loops from each coil so that these loops enclose mainly the one coil, with a progressively smaller proportion of flux closure loops enclosing adjacent and further coils.

Alternatively, the spacers could be made from a non-magnetic but conducting material, such as copper, as long as the thickness of the spacers was sufficient so that at the magnetostrictive unit operating frequency, the skin depths of eddy currents in the spacers are sufficient to shield one coil from its neighbours.

Since a full size magnetostrictive rock drill may consume about 6 kW of electrical power, it follows that some of this power may be converted into heat within the magnetostrictive unit. This heat will have to removed by an active cooling circuit, since the performance of Terfenol-D deteriorates at temperatures above 150°C. Although not illustrated, the water may circulate in the steel outer case and/or in axially extending holes in the non-magnetic Tufnol plastic sleeve 14. Other cooling channels may be spaced circumferentially around the magnetostrictive unit. The metal spacers 16 help conduct

heat out of the coils towards the cooling circuits.

Returning now to the description of the drive and control electronics 11, each coil is provided with its own drive circuit, all of which operate at the same frequency. Each drive circuit generates a bipolar square wave, whose amplitude may be controlled. The magnetic field amplitude at the coil ends will naturally be less than in the centre of the coil arrangement because of fringing effects. The drivers at these end positions are therefore adjusted to boost the voltage to compensate the field amplitude.

As has been highlighted in the text and shown in Figure 1, the preferred embodiment uses two load sensing devices 15,24. Load cell 15 is mounted such that force generated by the actuator is presented onto the load cell 15. This in turn generates an electrical signal representative of force. This load cell 15 serves two purposes, initially it is used in the setup procedure of the actuator to ensure correct levels of prestress are set, whilst secondly, it allows monitoring of force generated by the actuator during operation of the actuator.

The second load cell 24 is mounted between the ram 10 and the actuator 4. This load cell monitors the force between the ram 10 and the rock face 1, as transmitted through the actuator 4. Hence the electrical signal from load cell 24 is the combination of the force generated by the ram and that of the actuator.

The electrical signal from load cell 24 is used in a closed loop control system 11 to regulate the force applied by the ram 10 onto the rock face 1. The force generated by the ram may be set such that the net force from the ram and the pulsating force from the actuator is

set at the optimum to fracture the rock type being drilled.

The control system mentioned above also allows control over the hydraulic motor. The motor/gearbox assembly 7,8 incorporates a shaft encoder and so a signal representative of rotational speed may be determined.

In the described embodiment the control system 11 is operated via a control computer (not shown). The computer issues commands for a specific rotational speed and force to be maintained on the drill bit to two control circuits, one in the rotary drive control unit and the other in the ram control unit. The control computer is also capable of operating a pump to flush water down the drill rod for cooling, and debris removal at the drill bit.

The control computer allows the operator to send specific control commands to the two the rotary and ram controllers, however the computer is capable of sequencing commands to the two controllers to operate the drill in a set sequence of rotation speeds and ram pressures.

An example of a drill sequence is first to find the start of the rock face, then retract the ram slightly to allow the motor to start prior to engaging the drill bit on the rock face, and then switch on the actuator. The flushing water is then turned on, and a force request sent to the ram. The drill rig then drills for a specified time period, following which the ram, motor, actuator and flushing water are switched off to complete the drill sequence.

It may, of course, alternatively be possible to implement at least some of this control in an open loop system with

an operator manually adjusting the ram and the hydraulic motor.

An important aspect of the embodiment described here is the nature in which the force from the actuator is applied. In this system the actuator force is applied in parallel with the force from the ram. The alternative to this system is to apply the force from the ram in series, that is, with the ram pushing through the magnetostrictive actuator.

The embodiment described has several advantages over the series system. Prestress on the actuator is a controllable parameter, and may be set to the optimum for the actuator, whereas in the series system the prestress is governed by the force generated by the ram. As the actuator performance is affected by the level of prestress, in the series system the total force that should exerted by the ram should be set such that it is a compromise between the optimum ram force for drilling and the optimum prestress level for the actuator. In the dynamic situation during drilling, the force exerted by the ram will rapid fluctuate as the rock fractures. Since the control system will in general exhibit a slower response time in tracking these changes, in the series system the prestress would be constantly changing from the optimum level.

In contrast, in the parallel system the prestress level is independent of ram force, hence both the actuator and the ram may be set to a more optimum level to fracture rock.

Another advantage of this system is that the total force generated by the ram is not transferred through the

magnetostrictive material. This is a useful characteristic, because it reduces the chance of the actuator being damaged in the event of the control system failing.

Finally, the parallel system allows use of a greater range of magnetostrictive material rod diameters. In the series system the prestress is governed by the force applied by the ram, hence this would preclude the use of an actuator whose prestress requirements were in excess of those that the ram could generate.

Finally, the rotation rate of the rotary unit 7,8 may optionally be synchronised with the frequency of the coil drive 11, so that as the coil drive frequency increases, so does the speed of the rotary unit.

Because the magnetostrictive unit 4 is held rigidly in position, the axial expansion of the Terfenol-D rod 13 causes the drill rod 3 and the drill bit 2 to be forced against the rock 1 to cause high local stresses in the rock, leading to fracturing.

When the magnetic field in the coils 12 is pulsed, ie repeatedly turned on and off, then the repeated expansion and contraction of the rod 3 will produce a pulsating action of the bit 2 against the rock, and this will produce a drilling action, especially when combined with rotation of the bit 2 through the rotary drive 7,8.

It is a property of magnetostrictive materials, that when the magnetic field is removed, the material returns to its original shape without requiring any externally imposed restoring force. The return to original shape may be accompanied by some hysteresis. In the preferred

embodiment of the invention, there is in fact an externally imposed restoring force resulting from the pressure exerted by the pre-stress spring assembly 18 continually compressing the Terfenol-D rod.

The magnetostrictive material will be prepared so that it has a preferential axial extension, when placed in a magnetic field. The dimensions of the magnetostrictive rod 13 will be determined, inter alia, in accordance with the hardness of the rock being drilled and the diameter of the hole to be drilled. It is expected however that in general the length of the rod will be from 250 mm to 1000 mm and that the diameter of the rod will be from approximately 20 mm to 80 mm. Diameters significantly lower than 20 mm may offer insufficient power for rock drilling, although may be suitable for other applications. Diameters larger than 80 mm may be desirable, but the cost of such large diameter magnetostrictive material may be too high. In general, diameters of the order of 80 mm will be used for harder rock. The length of the rod may be increased by abutting and gluing rods end to end, and larger diameter rods may be formed by cutting rods into a hexagonal cross section, and then gluing rods side by side.

Rods may also be cut lengthwise into several strips, and then laminated together with insulating glue, in order to reduce shielding skin effects due to eddy currents, and so improve high frequency performance. For example, at 2 kHz, the skin depth δ of Terfenol-D having a relative permeability μ_r of 2 to 5 and a conductivity κ of $1.6 \times 10^6\ \Omega^{-1}m^{-1}$ is 6.4 mm to 4.2 mm. Accordingly, at 80 kHz, the skin depth would be typically in the range 1.0 mm to 0.67 mm. Since the drive current may contain frequency components above a 2 kHz drive frequency, a 20 mm diameter

Terfenol-D rod may be laminated from 2 mm thick slices.

For some types of rock drilling, however, a high frequency may not be necessary. For example, satisfactory results have been obtained in softer types of rock at frequencies as low as 30 Hz, which is comparable to the frequencies used in conventional hydraulic hammer drills. Higher frequencies, of the order of 1 kHz or 2 kHz, may be usefully employed in hard rock drilling.

The efficiency of magnetostrictive materials in converting externally provided energy to an axial force is high compared with the corresponding efficiency of hydraulic mechanisms. Furthermore the pulsating force applicator only requires connection in an electrical circuit, and electrical cables can in some circumstances be handled more easily than hydraulic hoses. The actuator described therefore makes use of the magnetostrictive effect to produce an effective and efficient apparatus for percussive or pulsating rock drilling.

Such an actuator may, however, find uses in other applications, for example as an actively controlled vibration damping or absorbing actuator, or in any applicator where high speed actuation is needed. One example of such an application is in the damping of vibrations in a bridge.

Claims

1. A magnetostrictive actuator for applying a pulsating pressure to a work piece, comprising a percussive tool for working the workpiece, biasing means arranged to apply a biasing force to the tool for biasing the tool against the work piece, a magnetostrictive unit arranged to apply a repetitive pulsating force to the tool for working the workpiece, the magnetostrictive unit having a length of magnetostrictive material and drive means for subjecting the material to a pulsed magnetic field to produce a change in the length of the material on each pulse of the magnetic field and so produce the pulsating force, wherein the arrangement is such that the biasing force is not transmitted to the tool through the length of magnetostrictive material.

2. A magnetostrictive actuator as claimed in Claim 1, in which the biasing means has a coupler arranged to bear upon the tool to bias the tool towards the work piece, the magnetostrictive unit being affixed the coupler.

3. A magnetostrictive actuator as claimed in Claim 2, in which the coupler has an aperture therethrough, and means to apply the pulsating force through the aperture to the percussive tool.

4. A magnetostrictive actuator as claimed in any preceding claim, in which the magnetostrictive material is pre-stressed along the length of the material when the drive means is not subjected to the pulsed magnetic field.

5. A magnetostrictive actuator as claimed Claim 4, in which the pre-stress is a compressive force along the

length of the magnetostrictive material.

6. A magnetostrictive actuator as claimed in Claim 5, in which the pre-stress is generated by a spring biasing means acting on an end of the magnetostrictive material.

7. A magnetostrictive actuator as claimed in any preceding claim, in which the drive means comprises a plurality of coils arranged to provide a magnetic field along the length of the magnetostrictive material.

8. A magnetostrictive actuator as claimed in any preceding claim, in which the ends of the magnetostrictive material bear against end pieces, one of the end pieces being fixed and another of the end pieces being movable upon a change in the length of the magnetostrictive material in order to apply the pulsating force to the percussive tool.

9. A magnetostrictive actuator as claimed in Claim 8, in which the magnetostrictive material is held within a sleeve which is close fitting around the sides of the material and open at the ends, the ends of the sleeve being held between the end pieces.

10. A magnetostrictive actuator according to any preceding claim, in which the drive means pulse current through coils in both positive and negative directions in order to double the frequency of the pulsating force relative to the drive frequency of the pulsed current.

11. A magnetostrictive actuator according to any preceding claim, in which the drive means actuate coils with drive current at different times to produce a

travelling wave pulse along the length of the magnetostrictive material.

12. A magnetostrictive actuator as claimed in any preceding claim, in which the magnetostrictive unit comprises a gauge to measure the pressure of the pulsating force and feedback means for controlling the pressure applied by the magnetostrictive unit, in which the gauge provides a signal representative of the pulsating pressure to the feedback means which then uses this signal to control the pulsating pressure.

13. A magnetostrictive actuator according to any preceding claim, in which the magnetic field is pulsed at a frequency of at least 30 Hz.

14. A magnetostrictive rock drill, comprising a percussive tool for working a rock face, and a magnetostrictive actuator as claimed in any preceding claim.

15. A magnetostrictive rock drill according to Claim 14, in which the biasing means includes a ram to provide the biasing force.

16. A magnetostrictive actuator substantially as herein described, with reference to or as shown in the accompanying drawings.

17. A magnetostrictive rock drill substantially as herein described, with reference to or as shown in the accompanying drawings.

The Patent Office

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Application No:	GB 9717022.9	**Examiner:**	Peter Easterfield
Claims searched:	1 to 15	**Date of search:**	27 October 1998

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.P): H4J (JCD)

Int Cl (Ed.6): B06B 1/08; B25D 11/00, 11/02, 11/04, 11/06, 16/00; B28D 1/14; E21B 1/00, 4/04, 4/12, 6/00; H01L 41/12

Other: Online: WPI, JAPIO, CLAIMS

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
A	WO 97/26090 A1 (BOART LONGYEAR)	

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
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